AFRL-HE-WP-SR-2001-0010

UNITED STATES AIR FORCE RESEARCH LABORATORY

The Effects of Head Orientation on Head/Helmet Vibration Response

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May 2001

Final Report for the Period October 1983 to September 1998

20011017 005

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AFRL-HE-WP-SR-2001-0010

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2001	Final - October 1983 to September 1998

4. TITLE AND SUBTITLE
The Effects of Head Orientation on Head/Helmet Vibration Response

5. FUNDING NUMBERS
PE - 62202F
PR - 7184
TA - 718443
WU - 71844308

6. AUTHOR(S)

Suzanne D. Smith

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Crew System Interface Division
Aural Displays and Bioacoustics Branch
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7901

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-HE-WP-SR-2001-0010

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
bioengineering, biomechanics, computerized simulation, ejection seats, helmets, injuries, mathematical model

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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THE EFFECTS OF HEAD ORIENTATION ON HEAD/HELMET VIBRATION RESPONSE

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ABSTRACT

Involuntary head/helmet motion due to vibration can compromise the effective use of helmet-mounted cueing systems. Extreme off-axis head/helmet orientations are also expected during tactical maneuvers where aircraft vibration occurs. The effects of head/helmet orientation on head/helmet low frequency vibration response were investigated. Subjects were exposed to an experimental F-15 vibration signal and to sinusoidal frequencies in the range of 3 to 10 Hz. Head and helmet rms accelerations, power spectral densities, and transmissibilities were evaluated. The results showed that head/helmet orientation had minimal effect on the frequency location of the peak responses, which primarily occurred between 4 and 7 Hz for both types of exposures. However, significant increases in the peak helmet pitch responses were observed for head/helmet orientations not aligned with the vertical input axis at the seat. For these off-axis orientations, both exposures showed responses, which tended to be higher at most frequencies below 10 Hz. These head/helmet response characteristics can provide important criteria for developing hardware damping mechanisms and/or software algorithms, which minimize the effects of head/helmet motions on tracking performance and cueing system stability.

INTRODUCTION

Military tactical aircraft are designed with flight maneuverability in order to optimize performance and survivability in hostile environments. However, these maneuvers can generate extreme aerodynamic forces on the aircraft which, in turn, are transmitted to the occupant. For example, during low speed, high angle of attack maneuvers, the F-15 aircraft can exhibit substantial buffeting. This buffeting has been characterized as vibration occurring at frequencies below 10 Hz. The human body is most sensitive to these frequencies, and some low frequency vibration can become amplified as it is transmitted to the upper torso and head of the pilot. Numerous studies have shown that vertical, horizontal, and pitch motion of the head can be increased to levels significantly above the vertical input motions at the seat during low frequency vibration exposure in the vicinity of whole-body resonance (4 to 8 Hz) (Mertens, 1978; Wilder, et al., 1982; International Standards Organization, 1987; Hinz and Seidel, 1987; Paddan and Griffin, 1988; Smith, 1996). Head motion can also be influenced by the head position or orientation during vertical vibration exposure. Griffin et al. (1978) found that looking upward tended to increase the vertical seat-to-head transmissibility while Cooper (1986) showed that raising or lowering the head increased head pitch vibration. A limited number of studies have shown that the addition of helmet systems can affect the motion at the helmeted head. Lewis (1979) showed that the addition of a flight helmet increased the transmission of vibration to the head between 7 and 20 Hz and attenuated the motion above 20 Hz with the use of a hard helicopter seat with seatback. The author also observed that, under similar seating conditions, head pitch transmissibility occurring between 7 and 14 Hz was attenuated while peaks observed at higher frequencies were increased with the addition of the flight helmet. Below 7 Hz, the helmet had little effect (Lewis, 1979). In a more recent study, Butler (1992) showed that increasing both the helmet system mass and the distance between the center-of-mass of the head and helmet significantly increased head and neck pitch accelerations below 10 Hz with the use of a helicopter seat. No change was observed in the frequency location of the first resonance peak, which occurred between 3 and 6 Hz. The author concluded that the head/neck system may have been actively controlled by neck muscles; that is, the head/neck system was not passive.

This paper was received for review on 13 May 1999 and was accepted for publication on 27 July, 1999.

One consequence of increased low frequency vibration transmission to the head is degradation in visual performance. With the use of helmet-mounted displays, these effects can be even larger due to such factors as the ineffectiveness of compensatory eye movement (at very low frequencies) and relative motion between the head and helmet-mounted display. Another important consequence of low frequency aircraft buffeting is related to the performance of helmet-mounted cueing systems, especially the head position/orientation tracking system. Helmet-mounted cueing systems (HMCS) were designed to optimize the identification and designation of targets during air-to-air confrontation. The HMCS uses the position of the head/helmet to locate a target and command the weapon system to the head/helmet line-of-sight (LOS) as it follows the target. This activity allows the pilot to rapidly align offensive targeting sensors onto any adversarial aircraft without the need to maneuver his/her aircraft. However, involuntary head/helmet motion caused by aircraft vibration, particularly during buffeting, has been associated with instability in the head/helmet LOS information, rendering it difficult to align the weapon system sensors' LOS with the designated target. Involuntary head motion may be substantially influenced by the extreme head/helmet orientations expected as the pilot tracks the target during tactical maneuvers. The inability to quickly acquire and designate targets threatens the survivability of tactical aircrews. One obvious but difficult solution for minimizing both visual performance and cueing system performance degradation is to physically minimize low frequency vibration transmission to the head/helmet system. A potential solution for improving cueing system performance is to develop software algorithms, which will filter the vibratory motion. Any successful solution requires the understanding of the head/helmet motions expected to occur during low frequency vibration and the influence of head/helmet orientation on the response characteristics. The objective of this study was to conduct a preliminary investigation to quantify and evaluate head and helmet system multi-axis motion for selected head/helmet orientations during exposure to seated vertical vibration. The ultimate goal is to improve the performance of helmet-mounted systems in buffeting and other vibration environments.

MATERIALS AND METHODS

An Unholtz-Dickie single-axis electrodynamic vibration platform was used to generate the vertical (Z-axis) vibration. A rigid human test seat was mounted on top of the platform. The seat included a seatpan and seatback oriented at 90 degrees and weighing approximately 12 kg. A double-strap shoulder harness and lap belt were used to restrain the subject. The lapbelt was snug but not tight. The shoulder harness was worn loose. This configuration was used to minimize any effects of the restraint system on body response. A flat seat cushion fabricated from rate-sensitive foam (approximately 3 cm in thickness) was placed between the subject and the hard seating surface (H. Koch & Sons; PN 99449/194-870026-1 REV and PN 99449/144-870041-1 REV.) The cushion weighed 1678.5 gm and was encased in cotton material with the top and side surfaces covered with a 2.5 cm thick fleece fabric. Accelerometer packs were attached to the top and back of the helmet, and to a bitebar for measuring the translational motion of the head. The packs included three orthogonally-arranged miniature accelerometers encased in a plastic disk with a diameter of 1.9 cm and a thickness of 0.86 cm. An accelerometer was attached beneath the rigid seat to measure the vertical input acceleration. A helmet-mounted cueing system was provided by Boeing (McDonnell Aircraft and Missile Systems) and included a modified HGU-55/P helmet and Polhemus magnetic tracker system. No oxygen mask was used in the study. Since only one helmet size was available, helmet foam pads were used to improve helmet fit/comfort as needed.

Boeing provided an acceleration power spectral density (PSD) measured on an F-15 aircraft. Two CSI 1900 Hand Held Vibration Analyzers were used to collect the peak acceleration levels occurring during selected aircraft maneuvers. Details on how these data were used to generate the PSD were unknown. However, the PSD provided by Boeing for the aircraft vertical accelerations was used to generate a 16-second vibration profile containing frequencies in the critical region of 3 to 10 Hz. Since details about the data were not available, and since the acceleration levels were relatively low compared to the levels estimated from previous aircraft structural data, the overall acceleration level of the profile was increased from approximately 0.08 g rms to 0.25 g rms. This was done to simulate a vibration environment more representative of the expected buffeting conditions and to more closely align with the aircraft structural data. Each frequency component was multiplied by a constant in order to maintain the profile shape of the original signal. The resultant experimental F-15 signal contained a peak-to-peak acceleration of 1.7 to 1.8 g's and crest factor (ratio of peak g to rms g) of 3.4 to 3.5. Although data were collected at both acceleration levels (0.08 and 0.25 g rms), only the results for the higher acceleration level are reported in this paper. Subjects were also exposed to discrete sinusoidal frequencies between 3 and 10 Hz in

1-Hz increments at a constant acceleration level of 0.10 g rms for comparison. For the experimental F-15 exposures, all transducer data were collected for 16 seconds. The acceleration data were low-pass filtered at 100 Hz and digitized at 1024 Hz. For the sinusoidal exposures, data were collected for two seconds at each frequency, low-pass filtered at 100 Hz, and digitized at 1024 Hz.

For the experimental F-15 exposures, the overall rms acceleration was calculated from the time histories. The power spectral densities of the input, helmet, and head accelerations and the cross spectral densities between the helmet and head accelerations and the input acceleration were calculated using Welch's Method (Welch, 1967). Welch's Method uses the discrete-time Fourier transform (Fast Fourier Transform or FFT) to estimate the spectral density (periodogram). The time histories were divided into segments of two seconds each (2048 points) with a 50 percent overlap. Following the application of a Hanning window, the periodogram of each segment was calculated and the results averaged for the signal. An estimate of the transfer function $H(\omega)$ between the input signal (A) and output signal (B) was calculated as the ratio between the cross spectral density, $P_{AB}(\omega)$, and the input power spectral density, $P_{AA}(\omega)$, as follows:

$$H(\omega) = \frac{P_{AB}(\omega)}{P_{AA}(\omega)} \quad (1)$$

The input signal (A) was defined as the vertical (Z) input acceleration measured at the seat. The output signals (B) were defined as the output accelerations at the head or helmet in each of the three translational axes (X or fore-and-aft, Y or lateral, and Z or vertical). The head and helmet transmissibility frequency responses between the head and helmet output accelerations and the input acceleration at the seat were calculated from the absolute value of $H(\omega)$. The coherence function, $C_{AB}(\omega)$, which is a measure of the degree to which the output (*B*) is caused by the input (*A*), was also calculated for the experimental F-15 exposures as follows:

$$C_{AB}(\omega) = \frac{\left|P_{AB}(\omega)\right|^2}{P_{AA}(\omega)P_{BB}(\omega)} \quad (2)$$

For the sinusoidal data, the FFT was applied to the resultant two-second acceleration time history. For each discrete frequency, the head and helmet transmissibility frequency responses were calculated as the magnitude ratio between the head and helmet output accelerations in each of the three translational axes, and the input acceleration at the seat.

Helmet pitch transmissibility was calculated for both the experimental F-15 and sinusoidal exposures. For the experimental F-15 exposures, the pitch acceleration (a_{PITCH}) was estimated as the difference between the longitudinal (Z) acceleration time histories measured at the helmet top ($a_{Z(TOP)}$) and helmet back ($a_{Z(BACK)}$) divided by the length of the moment arm (*d*) between the two measurement sites:

$$a_{PITCH}(t) = \frac{\left(a_{Z(TOP)}(t) - a_{Z(BACK)}(t)\right)}{d} \quad (3)$$

where *t* is time. The length of the moment arm (*d*) was estimated from photographs of the instrumented helmet. Welch's Method was applied to calculate the helmet pitch transmissibility between the helmet pitch acceleration and vertical input acceleration at the seat in accordance with Eq. 1 where (A) represents the vertical input acceleration and (B) represents the helmet pitch acceleration. The helmet pitch coherence was calculated in accordance with Eq. 2. For the sinusoidal exposures, the helmet pitch was calculated as the difference between the complex accelerations measured at the top and back of the helmet divided by the moment arm, *d*. The sinusoidal helmet pitch transmissibility frequency response was calculated as the magnitude ratio between the resultant helmet pitch acceleration and input acceleration at the seat. It should be noted that the units of the helmet pitch transmissibility are radians/s^2 per m/s^2 (rad/s^2 / m/s^2).

Six subjects (including three females and three males) were used in the study. TABLE 1 lists the weight of each subject. The weights of the females fell within the 3rd and 90th percentiles for weight among female military personnel (Gordon, et al., 1989). The weights of the males fell within the 10th and 80th percentiles for weight among male military personnel (Gordon, et al., 1989). Measurements were made for four head/helmet orientations as defined in TABLE 2. Spherical balls were mounted in the test area at the specified headings to

Table 1. Subjects

FEMALE SUBJECTS	WEIGHT (Kg)
Subject 1	49.2
Subject 2	62.6
Subject 3	71.7
MALE SUBJECTS	WEIGHT (Kg)
Subject 4	65.8
Subject 5	76.7
Subject 6	85.7

Table 2. Head/Helmet Orientations

ORIENTATION (ORT)	ELEVATION	AZIMUTH
	(Degrees)	(Degrees)
A	0	0
B	+40	+70
C	0	+70
D	+40	0

establish the head/helmet orientations. The subjects used the crosshairs displayed on the helmet-mounted system to aim at the spherical ball and were asked to try and maintain the crosshairs on the ball during data collection. The heading provided by the cueing system was recorded for each orientation. The head/helmet orthogonal coordinate system changed with respect to the input coordinate system at the seat depending on the head/helmet orientation. All measurements and calculations reported for the head and helmet were relative to the anatomical coordinate system of the head (fore and aft, lateral, and longitudinal), while the vertical input calculations were relative to the seat coordinate system. The head/helmet anatomical coordinate system was used to provide a more meaningful comparison of head and helmet biodynamics between orientations. The head and helmet accelerations can be transformed to the seat coordinate system using the information provided in TABLE 2. The subjects were also instructed to maintain an upright seating posture with their spine in contact with the seatback as much as possible.

Comparisons were made between the overall rms accelerations and between the frequency response characteristics (power spectral density and transmissibility) for each translational axis, measurement site (helmet top, helmet back, head), and head/helmet orientation. The transmissibility resonance frequency was defined as the frequency location of the peak transmissibility at the respective measurement site. Resonance frequency and frequency location of the peak response are used interchangeably in this paper. Data from the six subjects were used to calculate the mean transmissibility resonance frequency and mean peak transmissibility magnitude. The helmet pitch power spectral densities and transmissibilities were also assessed for orientation effects. The Repeated Measures Analysis of Variance (ANOVA), Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method), and Paired *t*-Test were used to determine significant differences in the acceleration rms levels, resonance frequencies, and peak transmissibility magnitudes. The Alpha (α) value for all comparisons was 0.05.

RESULTS

Overall rms accelerations

Figure 1 illustrates the mean +/- one standard deviation for the translational rms accelerations measured for the six subjects at each measurement site, axis, and head/helmet orientation (ORT) for the experimental F-15 exposures. Those locations marked with an asterisk indicate that the rms acceleration at the measurement site was significantly different as compared to the input rms acceleration. In the fore-and-aft direction, both the head and helmet measurement sites showed significantly higher accelerations at ORT's B and D as compared to ORT's A and C. Except for the helmet top (at ORT's B and D), all accelerations were equal to or less than the vertical input acceleration at the seat. Head/helmet translational motion in the fore-and-aft direction (relative to the head/helmet coordinate system) was expected for ORT's B and D since the longitudinal axis of the head/helmet was not aligned with the input vertical axis for these orientations. However, the head/helmet motions could be additionally influenced by head/helmet pitch vibration (regardless of any effects associated with relative head/helmet motion caused by helmet fit). For ORT's A and C, the fore-and-aft motion was associated primarily with head/helmet pitch vibration.

Differences in the lateral motion were most noticeable at the head, where significantly higher accelerations occurred for ORT B as compared to the other orientations and as compared to the two helmet sites. For the head/helmet coordinate system, lateral translation and roll and yaw rotation may have occurred for ORT B but were expected to be low for ORT's A, C, and D as reflected in the Y-axis acceleration data depicted in Figure 1. Given the large lateral motions measured at the bitebar and relatively low motions measured at the helmet top, it was speculated that the head motion was primarily affected by yaw rotation, although the location of the center of rotation was not clear. In order to achieve the heading associated with ORT B, the subjects rotated their heads backward (similar to ORT D) and about the longitudinal axis of the head while maintaining contact between the upper torso and seatback. For some subjects, it was observed that the helmet came in contact with the subject's shoulder or the edge of the seat back at ORT B. This may have restricted any excessive lateral motions of the helmet, but allowed the head to move relative to the helmet system under these conditions. ORT B was the

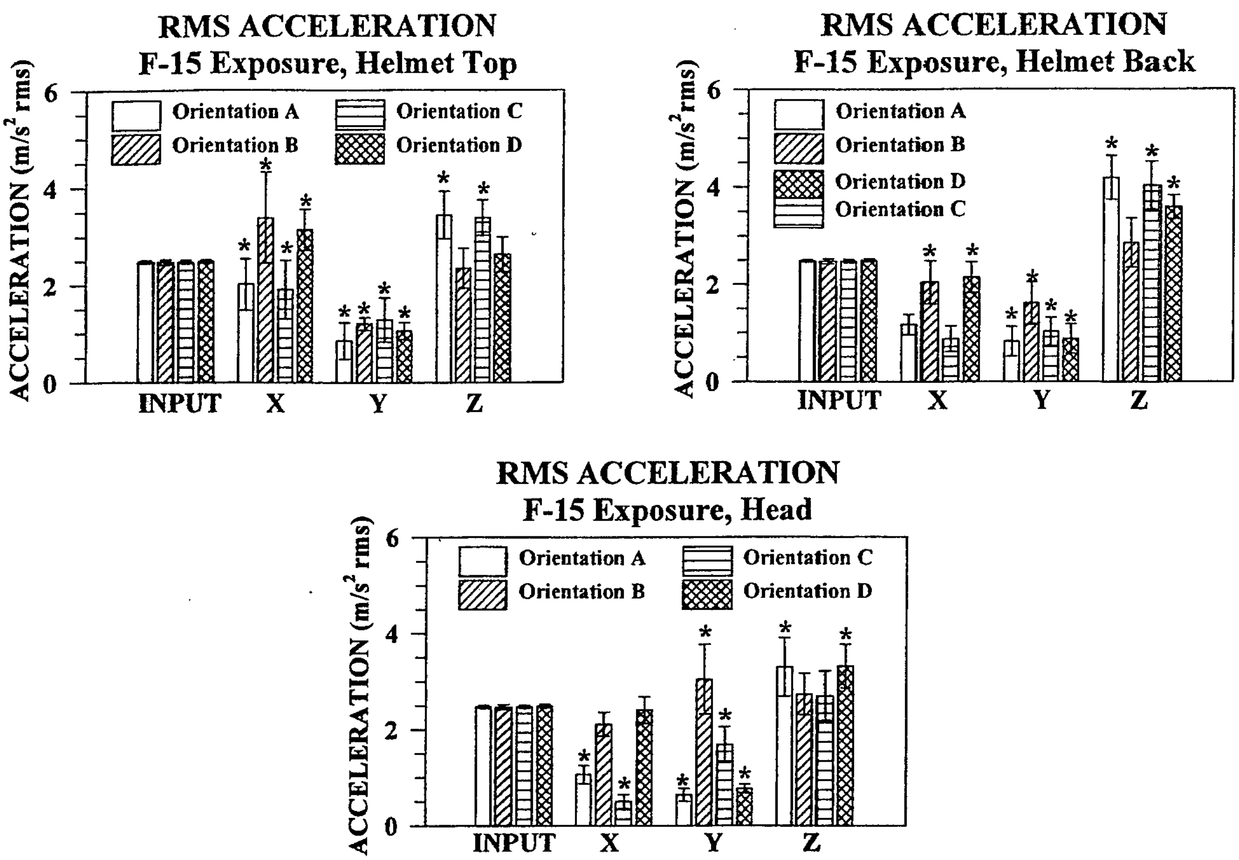

Figure 1. Mean rms Accelerations +/- One Standard Deviation for the Experimental F-15 Exposures

only orientation where all three head/helmet coordinate axes were not aligned with the seat coordinate axes. The head also showed significantly higher lateral motion at ORT C as compared to ORT's A and D. This may have been partially due to instability in the voluntary control of head position at this orientation.

For the vertical or longitudinal direction, the accelerations at the helmet sites showed similar trends, with the highest accelerations occurring for head/helmet orientations A and C. These accelerations were also higher than the input acceleration. For these two orientations, the head/helmet vertical axis aligned with the input vertical axis. Both the head and helmet back showed significantly higher motion for ORT D in the longitudinal direction as compared to the helmet top. This is in contrast to the higher fore-and-aft motions observed at the helmet top for ORT D, again suggesting the presence of head/helmet pitch motion.

Frequency response characteristics - translational motions

Figure 2 illustrates the vertical seat input acceleration power spectral density (PSD) for the experimental F-15 exposure. The figure shows that the greatest power in the input signal occurred between about 4 and 7 Hz. The highest peak in the input PSD occurred between 6 and 7 Hz, while a second (slightly lower) peak occurred at about 4 Hz. There was very little motion generated above 7 Hz. Although the peak input motion occurred between 6 and 7 Hz, the peak output motions at the helmet top, helmet back, and head consistently occurred at about 4 Hz in the fore-and-aft (X) and longitudinal (Z) directions. As an example, Figure 2 also shows the PSD's for the top of the helmet and head in the fore-and-aft, lateral, and longitudinal directions for the experimental F-15 exposures. For the majority of sites, the motion between 6 and 7 Hz was either similar to or less than the input motion between 6 and 7 Hz. For the lateral direction, the relatively larger motion observed at the head for ORT B in the rms acceleration data was reflected in the broad PSD peak occurring around 4 to 6 Hz, again, suggesting

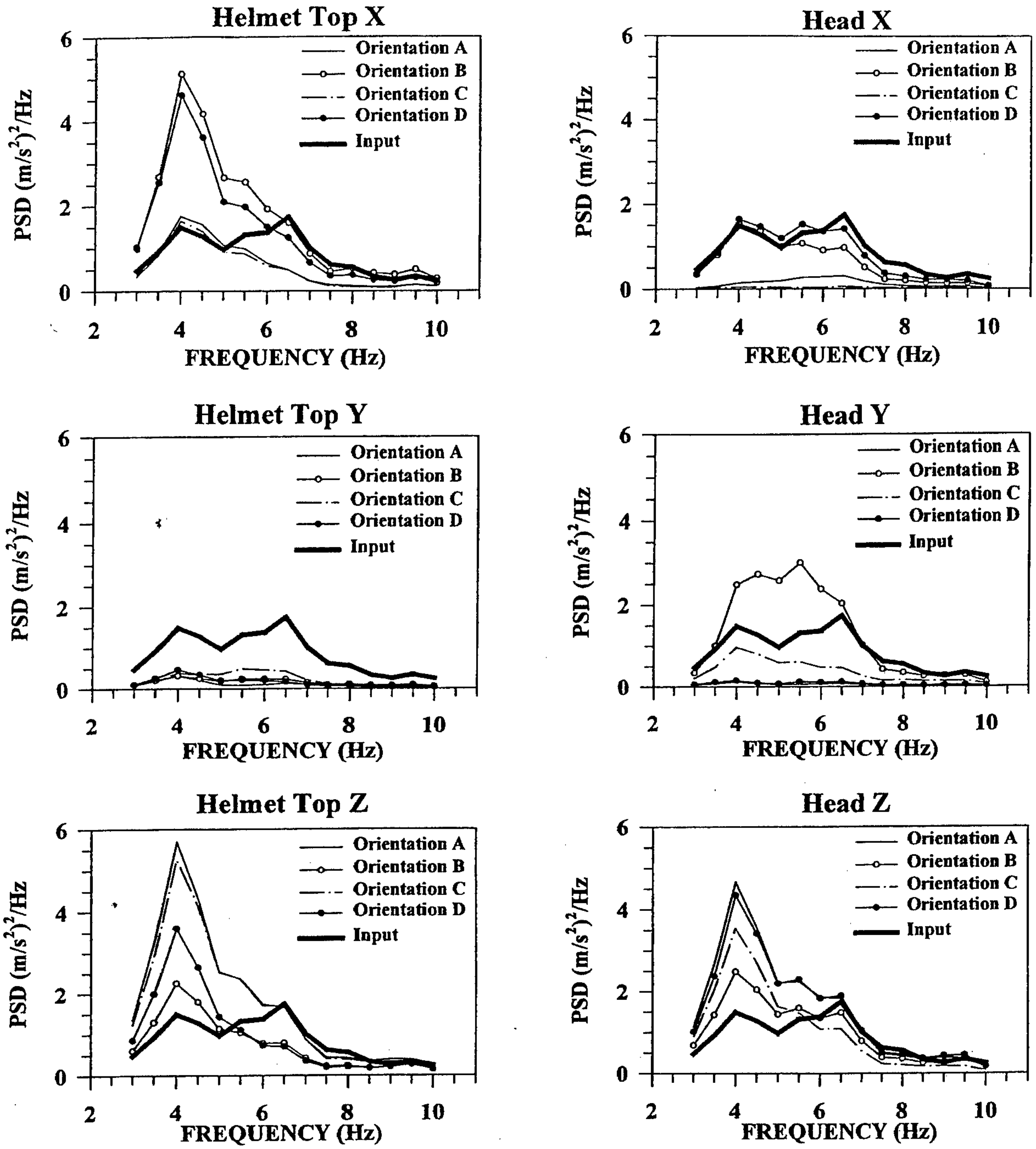

Figure 2. Vertical Input, Head, and Helmet Top Power Spectral Densities for the Experimental F-15 Exposures

relative head/helmet motion at this orientation.

The mean frequency location (resonance frequency) and mean magnitude of the peak head and helmet transmissibility responses were calculated from the transmissibility response data for the six subjects. Table 3 lists the *P* values for the one-way repeated measures ANOVA results for head/helmet orientation effects. The table includes the values for the resonance frequency and peak head and helmet transmissibilities.

For the majority of the experimental F-15 exposures, the mean transmissibility resonance frequency associated with the peak transmissibility response occurred around

TABLE 3 *P* Values for One-Way Repeated Measures Analysis of Variance – Head/Helmet Orientation Effects

P VALUE FOR ONE-WAY REPEATED MEASURES ANOVA				
Alpha (α)=0.05				
MEASUREMENT SITE/AXIS	F-15 EXPERIMENTAL EXPOSURE		SINUSOIDAL EXPOSURE	
	Peak Transmissibility Magnitude	Resonance Frequency	Peak Transmissibility Magnitude	Resonance Frequency
HELMET TOPX	0.005	0.042	<0.001	0.093
HELMET TOPY	0.558	0.203	0.030	0.010
HELMET TOPZ	<0.001	0.460	<0.001	0.529
HELMET BACKX	<0.001	0.106	<0.001	0.294
HELMET BACKY	0.015	<0.001	0.008	0.002
HELMET BACKZ	<0.001	0.134	0.149	0.306
HEADX	<0.001	0.010	<0.001	<0.001
HEADY	<0.001	0.637	<0.001	0.681
HEADZ	0.123	0.780	0.020	0.274
HELMET PITCH	<0.001	0.562	<0.001	0.670

4 Hz, similar to the peaks observed in the PSD's, with the mean frequencies ranging from 3.5 - 6.3 Hz. The transmissibility resonance frequency was observed to be as low as 3 Hz and as high as 9.5 Hz. Relative to the head/helmet orientation, the only significant differences in the resonance frequencies occurred at the head in the fore-and-aft (X) direction and at the helmet back in the lateral (Y) direction. For the head, a higher resonance frequency was observed in the fore-and-aft direction for ORT's A and C (means of 6.3 and 5.7 Hz, respectively), although there were significant variations among the subjects, particularly for ORT C. For the helmet back in the lateral direction, a higher resonance frequency was observed for ORT B (mean of 5.7 Hz).

Figure 3 illustrates the mean peak transmissibility responses +/- one standard deviation occurring during the experimental F-15 exposures for the six subjects. The trends in the peak transmissibility responses were similar to the results observed for the rms accelerations and power spectral densities. Both the head and helmet showed higher peak responses in the fore-and-aft direction for ORT's B and D. For these two orientations, the majority of sites showed peak fore-and-aft responses which were greater than the input and which reached values slightly over twice the input (particularly for the helmet top) at the respective frequency. In contrast, the helmet top and helmet back showed higher peaks in the longitudinal direction at ORT's A and C. However, the longitudinal peaks were similar at the head. The majority of the peak longitudinal responses were greater than the input, reaching values greater than two times the input (particularly for the helmet sites). In the lateral direction, the peak transmissibilities were significantly higher at the helmet back and head for ORT B, with the head showing the highest response. The peak response was also greater at the head for ORT C as compared to ORT's A and D, similar to the trends observed in the rms acceleration data. For the lateral direction, all peak responses were less than the vertical input except for the head at ORT B, which reached values approaching twice the input level. Although not illustrated, the transmissibility coherency was the greatest between 4 and 7 Hz and declined rapidly above 7 Hz. The head and helmet longitudinal transmissibilities showed the highest coherency occurring primarily above 0.9. The coherency associated with head and helmet fore-and-aft transmissibility occurred primarily above 0.8. The head and helmet lateral transmissibilities showed the lowest coherency, primarily occurring above 0.7.

The mean resonance frequency for the sinusoidal exposures primarily occurred between 4 and 6 Hz. The lowest frequency was 3 Hz and the highest was 10 Hz. As observed for the F-15 exposures, the head showed a significantly higher transmissibility resonance frequency in the fore-and-aft direction for ORT C (mean of 8.3 Hz), while the helmet back showed a significantly higher resonance frequency in the lateral direction for ORT B (mean of 6.7 Hz). In addition, the helmet top showed a significantly higher resonance frequency in the lateral direction at ORT B as compared to ORT's A and C,

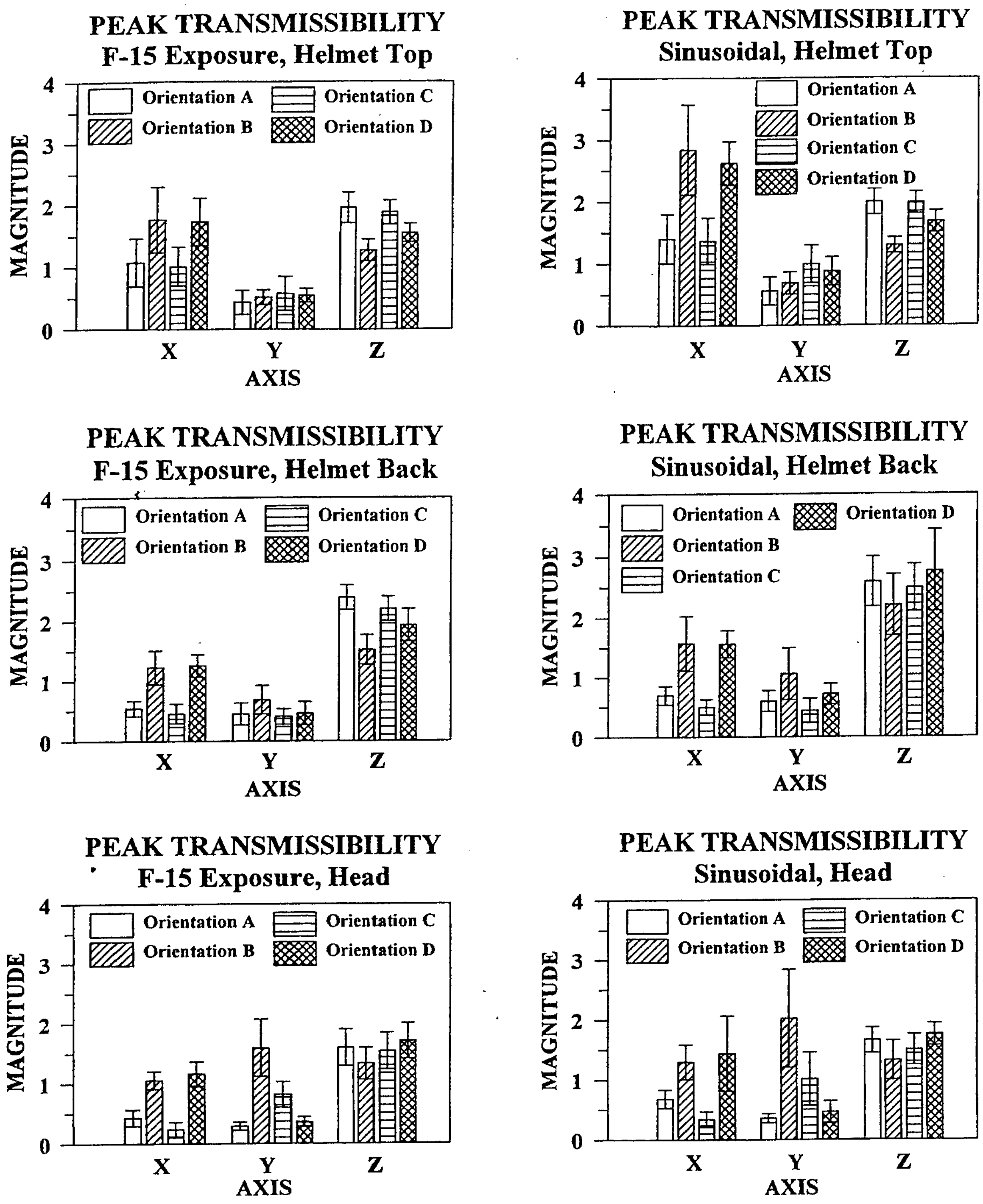

Figure 3. Mean Peak Translational Transmissibilities +/- One Standard Deviation for the Experimental F-15 and Sinusoidal Exposures

although there was relatively large variability between subjects.

Using the Paired *t*-Test, the resonance frequencies occurring for the experimental F-15 and sinusoidal exposures were compared in each axis at each measurement site. The majority of the comparisons showed similar results for the two exposures. Any differences were observed as higher resonance frequencies occurring for the sinusoidal exposures.

Figure 3 includes the mean peak transmissibility responses +/- one standard deviation for the sinusoidal exposures. The trends in the mean peak responses were similar to the trends observed for the experimental F-15 exposures. All measurement sites showed significantly higher peak responses in the fore-and-aft direction at ORT's **B** and D, while the helmet top showed significantly higher peaks in the longitudinal direction for ORT's **A** and C. The helmet back showed similar responses in the longitudinal direction, but the variability among subjects was relatively high. While the trends were similar as compared to the F-15 exposures, the head did show significantly higher motions in the longitudinal direction for ORT's A and D as compared to B. In the lateral direction, again, the helmet back and head showed significantly higher peaks for ORT B, with the head showing the highest and most dramatic response, reaching as high as three times the input at the seat. The higher response observed for the head at ORT C relative to ORT's **A** and D was not statistically significant. The helmet top did show a higher response at ORT C as compared to ORT A, but the transmissibilities were about 1.0 or below.

The Paired *t*-Test showed that the majority of the peak transmissibility responses were similar between the experimental F-15 and sinusoidal exposures. Any differences were observed as higher peak responses for the sinusoidal exposures. In particular, the differences were most pronounced for fore-and-aft motion at the helmet top and the longitudinal motion at the helmet back. In some cases, the peak sinusoidal motions of the helmet were greater than three times the vertical input level. The head showed the least differences between the two types of exposures. These results suggested that relative head/helmet motion was greatest for the sinusoidal exposures. However, some caution should be taken due to differences in signal processing between the two types of exposures (Welch's Method vs direct FFT calculation).

Frequency response characteristics - helmet pitch motions

Figure 4 illustrates the mean helmet pitch power spectral densities occurring during the experimental F-15 exposures for the six subjects at each of the four head/helmet orientations. The mean peak power spectral density for the helmet pitch accelerations tended to occur

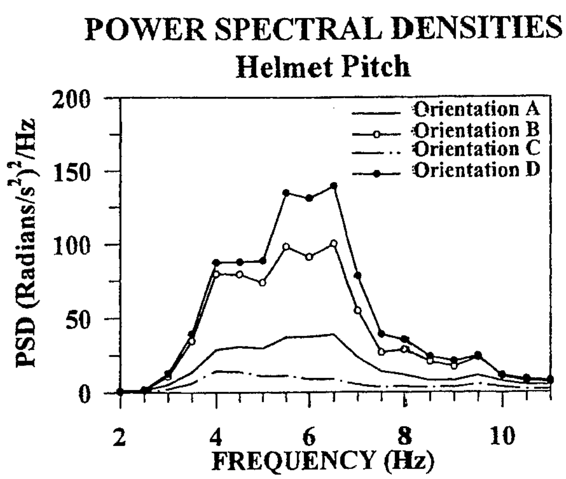

Figure 4. Mean Helmet Pitch Power Spectral Densities for the Experimental F-15 Exposures

at a higher frequency as compared to the translational motions, particularly for ORT's A, **B**, and D. The resonance frequencies were similar between head/helmet orientations. However, over 50 percent of the peaks occurred at 6.5 Hz, coinciding with the primary peak observed in the vertical input signal between 6 and 7 Hz. For these orientations, a second (lower) PSD peak was observed around 4 Hz, coinciding with the second peak observed in the vertical input PSD. While both ORT's B and D showed a significantly higher peak response as compared to ORT's A and C, the peak power spectral density at ORT D was significantly higher than at ORT B.

Figure 5 illustrates the mean resonance frequencies and peak helmet pitch transmissibilities occurring during the experimental F-15 exposures for the six subjects at each of the four head/helmet orientations. The resonance frequencies were similar when compared between head/helmet orientations. The mean pitch resonance frequencies fell within the same range observed in the translational transmissibilities, but tended to occur at the higher end of the range. The majority of responses occurred at 6 Hz or lower. These values were slightly lower than the frequency location of the peak PSD's. The peak helmet pitch transmissibility was significantly higher for ORT's B and D as compared to ORT's A and C, confirming the significant contribution of head/helmet pitch to the translational measurements at these two orientations. Except for one subject, the lowest helmet pitch transmissibility occurred for ORT C. Figure 6 illustrates the mean pitch transmissibility frequency responses at each of the four head/helmet orientations for

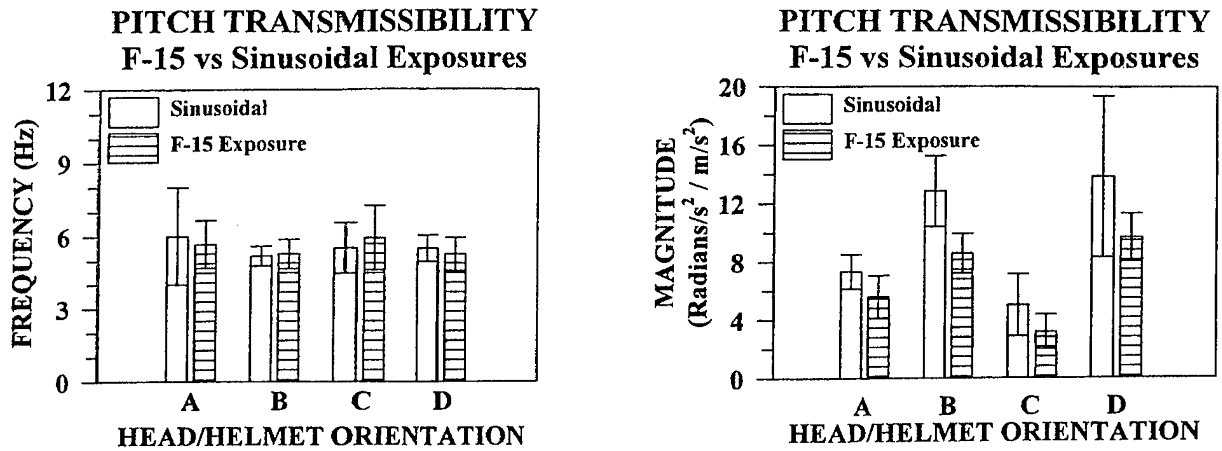

Figure 5. Mean Pitch Resonance Frequencies and Mean Peak Pitch Transmissibilities +/- One Standard Deviation – Experimental F-15 vs Sinusoidal Exposures

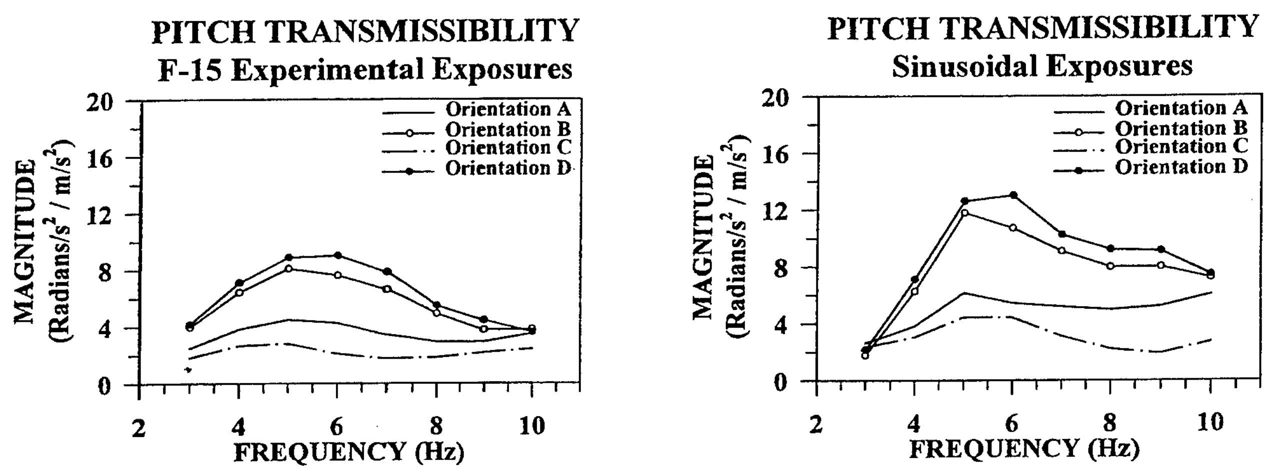

Figure 6. Mean Transmissibility Frequency Responses at Each Head/Helmet Orientation for the F-15 Experimental and Sinusoidal Exposures

the F-15 experimental exposures for the six subjects. The figure shows higher mean helmet pitch transmissibilities for ORT's B and D for most of the frequency range below 10 Hz. Unfortunately, sufficient data were not collected for calculating head pitch transmissibility. Therefore, it resonance frequencies were similar when compared was difficult to confirm the contribution of head pitch motion to the results and also difficult to assess relative head/helmet motion. The helmet pitch transmissibility coherence was primarily above 0.8 and declined rapidly above 7 Hz.

Figure 5 includes the mean resonance frequencies and mean peak helmet pitch transmissibilities calculated for the sinusoidal exposures. The pitch transmissibility between head/helmet orientations. The peak helmet pitch transmissibilities for ORT's B and D were significantly higher than the helmet pitch for ORT's A and C, similar to the results for the experimental F-15 exposures. ORT's A and C showed similar peaks. Figure 6 includes the mean helmet pitch transmissibility frequency responses for the sinusoidal exposures. The figure shows higher helmet pitch transmissibilities for ORT's B and D for most of the frequency range below 10 Hz, similar to the trends observed in the F-15 exposures.

The pitch resonance frequencies and peak transmissibility responses were compared between the experimental F-15 and sinusoidal exposures for each orientation using the Paired *t*-Test. The resonance frequencies between the orientations for the two types of exposures were similar. Although the peak helmet pitch transmissibility responses were similar for ORT A, Figures 5 and 6 show a tendency for lower values during the experimental F-15 exposure. The sinusoidal peaks were significantly higher than the peaks resulting from experimental F-15 exposures for ORT's B and C. The large variability in the peak pitch transmissibility for the experimental F-15 exposures at ORT D resulted in no statistically significant differences using the Paired *t*-Test. However, the results depicted in Figures 5 and 6 show that the responses tended to be higher for the sinusoidal exposures, again, possibly due to the signal processing techniques.

DISCUSSION AND CONCLUSIONS

There were several factors, which could have influenced the results of this study and the extrapolation of the data to the operational environment. For the preliminary study, only one size helmet with the helmet-mounted cueing system was available for use by all six subjects. All six subjects required the addition of foam pads at the top of the helmet liner and/or behind the ear cuffs. It was not known how the foam pads influenced helmet motion at the selected orientations. However, regardless of the variable requirements for the foam pads among the subjects, all subjects showed similar effects of helmet orientation. The use of a face mask could increase helmet stability and minimized relative head/helmet motion. However, a face mask would have interfered with the use of the bitebar for collecting head accelerations and could not be used in this study. In addition, inflation of a positive pressure breathing (PPB) system could also improve helmet stability. However, it was not clear to what extent the system would be inflated during operational buffeting. As mentioned previously, head pitch could not be calculated from the data collected in this study which would have allowed quantification of the relative head/helmet motion under the conditions used in this study. It should be noted that relative head/helmet motion was not severe enough to cause the subjects to lose the displayed crosshairs at any of the head/helmet orientations used in this study.

Seating posture/restraint is another factor, which may have influenced the results of this study relative to the operational environment. It is known that some pilots tend to lean away from the seatback and may either orient their upper torso or orient the aircraft towards the target. Paddan and Griffin (1988) found that a back off seating posture, while showing higher variability for vertical head transmissibility, did show lower fore-and-aft motion in the head. However, no differences were observed in the head pitch. It should be cautioned that these subjects were not wearing helmets. For the pilot, orienting towards the target could additionally minimize the difference between the head/helmet longitudinal axis and upper torso longitudinal axis and possibly reduce head/helmet motion at these orientations. Pilot head/helmet motion during actual F-15 tactical maneuvers is being investigated in this laboratory.

Since details about the F-15 data provided for this study were not available, it was uncertain to what extent the F-15 profile represented aircraft vibration specifically associated with buffeting. The profile showed substantial vibration in the vicinity of 4 to 7 Hz where the major resonance of the whole-body occurs. Higher transmissibilities have been observed at the head under similar testing conditions without the use of a helmet (Smith, 1996). Based on these observations, the similarity in the transmissibility characteristics associated with head/helmet orientation between the F-15 experimental exposures and the sinusoidal exposures was expected. If substantial aircraft buffeting occurs above or below whole-body resonance in very narrow frequency bands, the frequency location and magnitude of the peak head/helmet responses may be different than the peak responses observed in this study. However, based on the results shown in Figure 6, both types of exposures showed higher mean transmissibilities for ORT's B and D for most of the frequency range below 10 Hz. It is speculated that the orientation effects will be similar, particularly since buffeting has been associated with low frequencies below 10 Hz.

The head/helmet vibration characteristics observed in this study provide an estimate of operational effects. These measurements, particularly those associated with off-axis orientations, can be used as criteria for the development and validation of damping mechanisms and software algorithms for minimizing the effects of head/helmet motions.

ACKNOWLEDGMENTS

This project was partially funded by the Joint Helmet Mounted Cueing System Program at Wright-Patterson AFB OH. The author acknowledges the support of DynCorp, Inc., particularly Mr. Raymond Newman, in conducting this study.

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